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Chapter 10
Nonequilibrium Sediment Transport

Section I
Introduction

10-1. General

Nonequilibrium sediment transport refers to cases where the outflowing sediment discharge from a reach does not equal the inflowing sediment discharge to that reach. All five processes of sedimentation: erosion, entrainment, transport, deposition, and consolidation are active. The nonequilibrium sediment transport condition results in an unstable streambed elevation. In such cases a numerical sedimentation model provides the computational framework for analysis.

10-2. Specific Gage Plots

Nonequilibrium sediment transport results in either an aggrading or a degrading streambed. A simple graphical technique that is useful for quantifying the nonequilibrium condition is a specific gage plot, Figure 10-1. Such a graph is made by selecting a water discharge and plotting its stage versus time from the measured stage-discharge rating curves. When there is a definite trend over time, sediment inflow to the reach is not in equilibrium with sediment outflow.

10-3. Equilibrium versus Nonequilibrium Conditions

Although sediment transport formulas are used in an analysis of nonequilibrium conditions, there are significant differences between the calculations for equilibrium sediment transport and calculations for the nonequilibrium condition. Table 10-1 summarizes those differences. The words “equilibrium” and “nonequilibrium” in this table refer to the exchange of sediment particles between the flow field and the bed of the cross section. Whereas the bed is the only source of sediment to a sediment transport formula, the sources for a nonequilibrium sediment condition include the bed, upstream reach, tributaries, and bank caving.

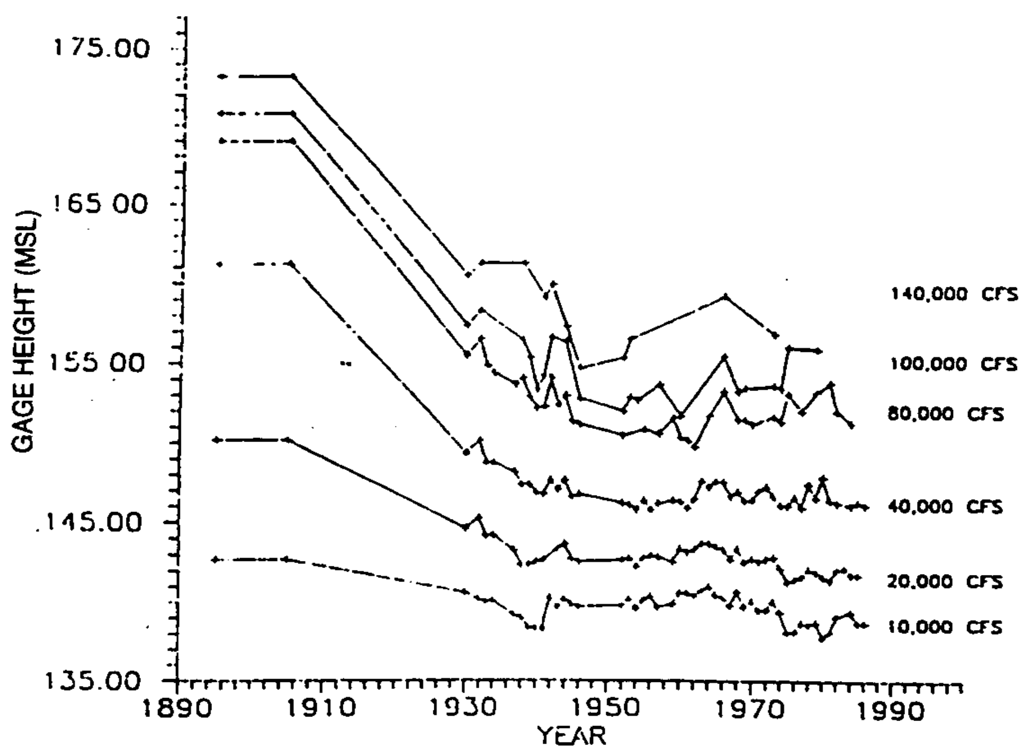

Figure 10-1. Specific gage plot

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Table 10-1
Differences Between Calculations for Equilibrium Sediment Transport and Nonequilibrium Sediment Transport

Sediment Discharge Formula	Nonequilibrium Models
Require flow intensity, bed roughness, particle density, and bed surface gradation	Require flow intensity, bed roughness, particle density, both surface and subsurface bed gradations, inflowing sediment load, geometry over long distances, and identification of bedrock outcrops.
Calculate the equilibrium condition	Calculate both the equilibrium condition and the changes in bed profile due to sediment inflow deficit or excess.
Functional only for the bed-material load	Functional for both bed-material and wash loads
	In the case of sand moving over a gravel bed, models will calculate both the quantity of sediment load moving and bed surface gradation required to sustain it

10-4. Mass Balance Models

The nonequilibrium condition is typically addressed using numerical sedimentation modeling. For most engineering studies, this modeling does not require tracing the motion of individual particles. Rather, it requires calculating the impact of flow intensity on bed particle behavior subject to particle size and availability. The objective is to calculate changes in the bed surface elevation in response to nonequilibrium sediment conditions and to feed those changes back into the calculation of the flow intensity-sediment load parameters. However, questions dealing with sediment quality often cannot be addressed without tracing the path of the sediment particles.

10-5. Numerically Modeling the Nonequilibrium Condition

The nonequilibrium problem can best be analyzed using a control volume approach. This allows the engineer to partition the river into reaches so both the bed and the inflowing sediment load to the reach are sediment sources to the calculations in that reach. Nonequilibrium conditions will transfer from one reach to the next because sediment movement tends to be highly variable in both discharge rate and particle size distribution. The most significant feature of a mobile-bed numerical model is its formulation of the sediment continuity equation which handles the exchange rate between the water column and the bed surface. It should account for sediment transport by size class and maintain a continuous account of the gradation in the streambed and on its surface. The numerical model should also account for: bed roughness, which can vary with discharge; bed armoring and sorting; bed surface thickness and porosity; and bed compaction. It should be recognized that there are major knowledge gaps related to sedimentation processes. For example, the lack of understanding of the bed sorting process and its effect on the transport of sediment mixtures makes it difficult to formulate a numerical representation of the process. Also, the fact that sediment is transported primarily in the channel requires that mobile bed computations maintain an accurate distribution of flow between the left overbank, channel, and right overbank at the cross section for which the computation is being made as well as a history of how the flow arrived at that location in the cross section whereas it is only necessary to balance energy in a fixed bed computation to solve for the water surface elevation.

Section II
Theoretical Basis

10.6. Equations of Flow and Continuity

The one-dimensional partial differential equations of gradually varied unsteady flow in natural alluvial channels are: (a) the equation of motion for the water-sediment mixture, (b) the equation of continuity for water, and (c) the equation of continuity for sediment. The system of equations for unsteady flow are established by considering the conservation of mass (both sediment and water) and momentum in an infinitesimal space between two channel sections.

Equation of Motion

$$\frac{\partial(\rho Q)}{\partial t} + \frac{\partial(\rho Q V)}{\partial x} + gA\,\frac{\partial(\rho\ y)}{\partial x} = \rho g A(S_o - S_f + D_l) \qquad (10\text{-}1)$$

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* Water Continuity

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q_w = 0 \tag{10-2}$$

Sediment Continuity

$$\frac{\partial Q_s}{\partial x} + (1-P)\,\frac{\partial A_d}{\partial t} - q_s = 0 \tag{10-3}$$

where

A = end area of channel cross section

A_d = volume of sediment deposited on the bed per unit length of channel

D_l = momentum loss due to lateral inflow

g = acceleration of gravity

P = porosity of the bed deposit (volume of voids divided by the total volume of sample)

Q = water discharge

Q_s = sediment discharge

q_s = lateral sediment inflow per unit length of channel, outflow (-), inflow (+)

q_w = lateral water inflow per unit length of channel, outflow (-), inflow (+)

S_f = friction slope

S_o = slope of channel bottom

t = time

x = horizontal distance along the channel

V = flow velocity

y = depth of flow

ρ = density of the water

10-7. Assumptions

The following assumptions are made in deriving these equations.

a. The channel is sufficiently straight and uniform in the reach so that the flow characteristics may be physically represented by a one-dimensional model.

b. The velocity is uniformly distributed over the cross section.

c. Hydrostatic pressure prevails at every point in the channel.

d. The water surface slope is small.

e. The density of the sediment-laden water is constant over the cross section.

f. The unsteady flow resistance coefficient is assumed to be the same as for steady flow in alluvial channels and is approximated from resistance equations applicable to alluvial channels or from field survey.

10-8. The Boundary Value Problem

With this system of equations there are three more unknowns than equations. The solution is obtained by prescribing the value of three variables on the inflow/outflow boundaries. This type of solution is called a boundary value problem. The boundary conditions are: (a) the water discharge, (b) the stage, and (c) the sediment concentration. These are prescribed for each point where water crosses the boundary of the study area. The solution of the system of equations is then possible. Depth, discharge, and sediment concentration at every computation point in the model can be calculated. The solution of the equations is deterministic, but the boundary conditions are not. It is important that the engineer select boundary conditions which depict historic behavior for model confirmation. Sometimes a different set of boundary conditions are required reflecting future conditions to model future prototype behavior.

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* *Section III*
Data Requirements

10-9. General Data Requirements

Two types of data are required for a numerical model study of a nonequilibrium stream. One type is used to define the behavior of the prototype. The other type is required to construct and adjust the numerical model. The first is summarized for completeness in this paragraph; the second is presented in more detail in following paragraphs. The ***project area and study area boundaries*** should be marked on a project map to delineate the area needing data. Lateral limits of the study area and the tributaries should be identified. ***Bed profiles*** from historical surveys in the project area are extremely valuable for determining the historical trends which the model must reconstitute. ***Aerial photographs*** and aerial mosaics of the project area are very useful for identifying historical trends in channel width, meander wave length, rate of bank line movement, and land use in the basin. ***Stream gage records*** establish the annual water yield to the project area and the water yield from it. They are also useful for establishing the hydraulic parameters of depth, velocity, roughness, and the trends in the stage-discharge curve in, or close to, the project reach. It is important to work with measured data. The "extrapolated" portion of a rating curve should not be regarded as measured data. Be aware that measured data are also subject to error. ***Reconnaissance of the project reach*** is a valuable aid for determining channel morphology, geometric anomalies, the existence of structures, and sediment characteristics of the channel. Include geotechnical and environmental specialists in a field reconnaissance if possible. Document these observations of the prototype in project reports. View as much of the prototype as is feasible and not just bridge crossings. ***Hydraulic data*** such as measured water surface profiles, velocities, and flood limits in the project reach are extremely valuable. Local action agencies, newspapers, and residents along the stream are sources of information when field measurements are not available.

10-10. Geometric Data

The purpose of mobile-bed calculations is to determine the water-surface elevation and the bed-surface elevation as they change over time. It is necessary to prescribe the starting geometry. After that, computations will aggrade or degrade the cross sections in response to mobile bed theory. The cross sections never change locations.

a. As in fixed bed calculations, it is important to locate the cross sections so that they model the channel contractions and expansions. It is particularly important in mobile boundary modeling to also recognize and set conveyance limits. That is, when flowing water does not expand to the lateral dimensions of a cross section in the prototype then conveyance limits should be set in the model.

b. There is no established maximum or minimum spacing for cross sections. Some studies have required distances as short as a fraction of the river width. Others have allowed spacing sections 10-20 miles apart. The objective is to develop a model that will reconstitute the historical response of the streambed profile. The usual approach is to start with the same geometry that was developed for fixed bed calculations. Note that, as most fixed bed data sets are prepared to analyze flood flows, they may be biased toward constrictions such as bridges and deficient of reach-typical sections that are important for long-term river behavior. There may also be cases when cross sections must be eliminated from the data set to preserve model behavior, such as a deep bend or junction section where the shape is molded by multi-dimensional hydrodynamics and not by one-dimensional hydraulic-sediment transport.

c. Use of river mile as the cross-section identification number is recommended. It is much easier to use or modify data when the cross sections are referenced by river mile rather than using an arbitrary section number.

10-11. Bed-Material Data

The bed-material reservoir is the space in the bed of the stream from which sediment can be eroded or onto which it can be deposited. This reservoir occupies the entire width of the channel, and in some cases the width of the overbank too. However, it might have 'zero' depth in the case of a rock outcrop. It is necessary to determine the gradation of sediment in that bed sediment reservoir and prescribe it for a numerical model. Bed-material sampling techniques are discussed in paragraph 8-13 of this manual. It is important to account for vertical, lateral, and horizontal variations in the bed-material reservoir. The gradation used in a numerical model should be "representative" of the reach and appropriate for addressing the engineering question at hand. For example, in one study two samples were taken in the dry at 27 cross sections spaced over a 20-mile reach of the creek. One was near the water's edge and the other was from the point
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* bar deposits about half the distance to the bank. These samples were sieved separately, and the resulting gradations plotted, as shown in Figures 10-2 and 10-3. Results from the water's edge samples were used to test for erosion because they were coarser than the midbar samples. The midbar samples were used to test for transport rates.

10-12. Hydrologic Data

Although instantaneous peak water discharges may be of interest, they are not adequate for movable bed analyses because time is a variable in the governing equations, and sediment volumes rather than instantaneous rates of movement create channel changes. Consequently, the water discharge hydrograph must be developed. This step can involve manipulations of measured flows, or it can require a calculation of the runoff hydrograph. Historical flows are needed to reconstitute behavior observed in the river, but future flows are needed to forecast the future streambed profile.

a. Hydrograph. The length of the hydrograph period is important. Trends of a tenth of a foot per year become significant during a 50- or 100-year project life. A long period hydrograph can become a computation burden. In some cases data compression techniques may be useful. As an example, Figure 10-4 shows how a year of mean daily flows could be represented by fewer discharges of larger duration. A computer program developed at WES, called the "Sediment Weighted Histograph Generator" was developed to preserve volumes while aggregating the energy of a varying hydrograph into extended numbers of days.

b. Tributaries. Tributaries are lateral inflow boundary conditions. They should be located, identified, and grouped as required to define water and sediment distributions. The locations should be shown on the cross-section locations. It is important that the water and sediment inflows from all gaged and ungaged areas within the study reach be included. Keep in mind that a 10 percent increase in water discharge could result in a 20 percent or greater increase in bed-material transport capacity. Often the tributaries are not gaged, thus requiring water distribution by analytical means. Drainage-area ratios may be used in some cases; however, use or development of a hydrologic model of the basin may be necessary.

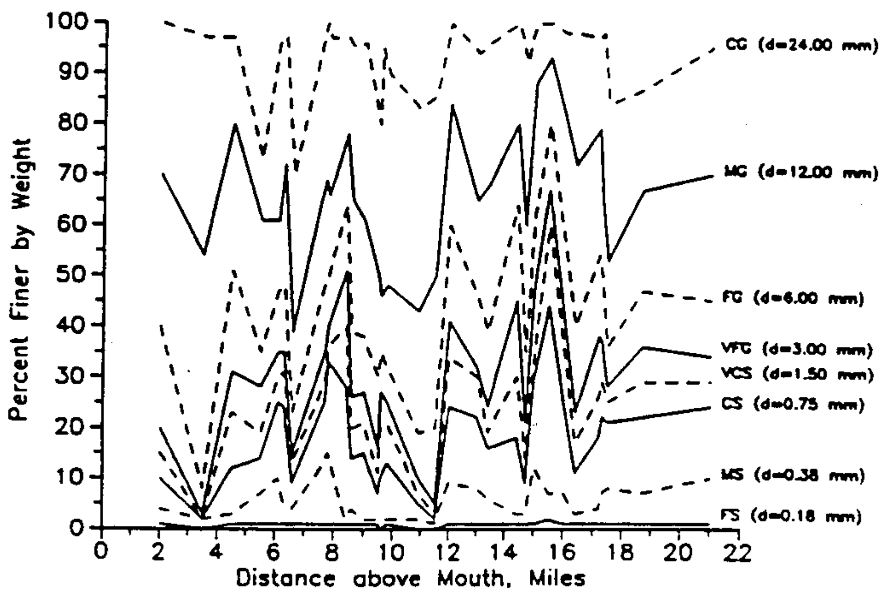

Figure 10-2. Bed-surface gradations based on water's edge samples

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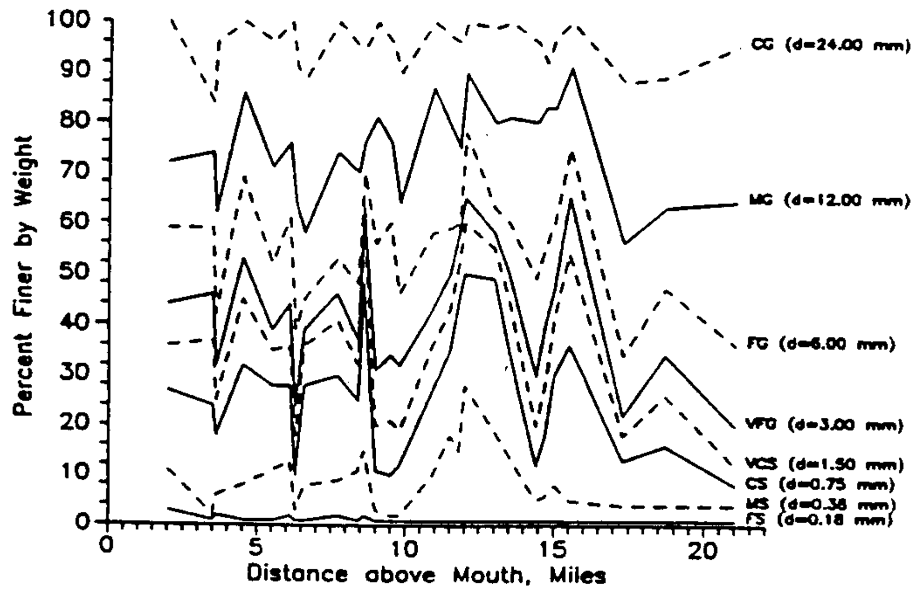

Figure 10-3. Bed-surface gradations based on midbar samples

Describe how inflows were accommodated for those tributaries not specifically included.

c. Tailwater elevation. The water-surface elevation at the downstream boundary of the project must be specified. It is referred to as a tailwater elevation because it serves the same purpose as a tailgate on a physical model. It can be a stage-discharge rating curve, or it can be a stage hydrograph. The rating curve can be calculated assuming normal depth if the boundary is in a reach where friction is the control and the water surface slope is constant for the full range of discharges. When a backwater condition exists, such as at the mouth of a tributary or in a reservoir, then use a stage hydrograph as the boundary condition. Be sure it covers the same period of time as the inflow hydrographs.

10-13. Sediment Inflow Data

a. Inflowing sediment concentrations. Occasionally, measured suspended sediment concentrations, expressed as milligrams per liter, are available. These are usually plotted against water discharge and often exhibit very little correlation with discharge; however, use of such graphs is encouraged when developing or extrapolating the inflowing sediment data. As the analysis proceeds, it is desirable in most situations to convert the concentrations to sediment discharge in tons/day and to express that as a function of water discharge as shown in Figure 10-5. A scatter of about 1 log cycle is common in such graphs. The scatter is smaller than on a concentration plot because water discharge is being plotted on both axes. The scatter may be the result of seasonal effects, random measurement errors, changes in watershed or hydrology during the measurement period, or other sources. The engineer should carefully examine these data and attempt to understand the shape and variance of the relationship.

b. Grain size classes. The total sediment discharge should then be partitioned into size classes for the mobile bed computations. Table 10-2 shows a procedure developed for the Clearwater River at Lewiston, Idaho. The data in this table come from measured bed load and measured suspended load. Figure 10-6 is the graph of that data set. Note that, due to the availability of various size fractions in the bed and the suspended load gradation for a given flow, the transport rate does not necessarily decrease with increasing particle size.

c. Calculating sediment inflow with transport theory. When no suspended sediment measurements are
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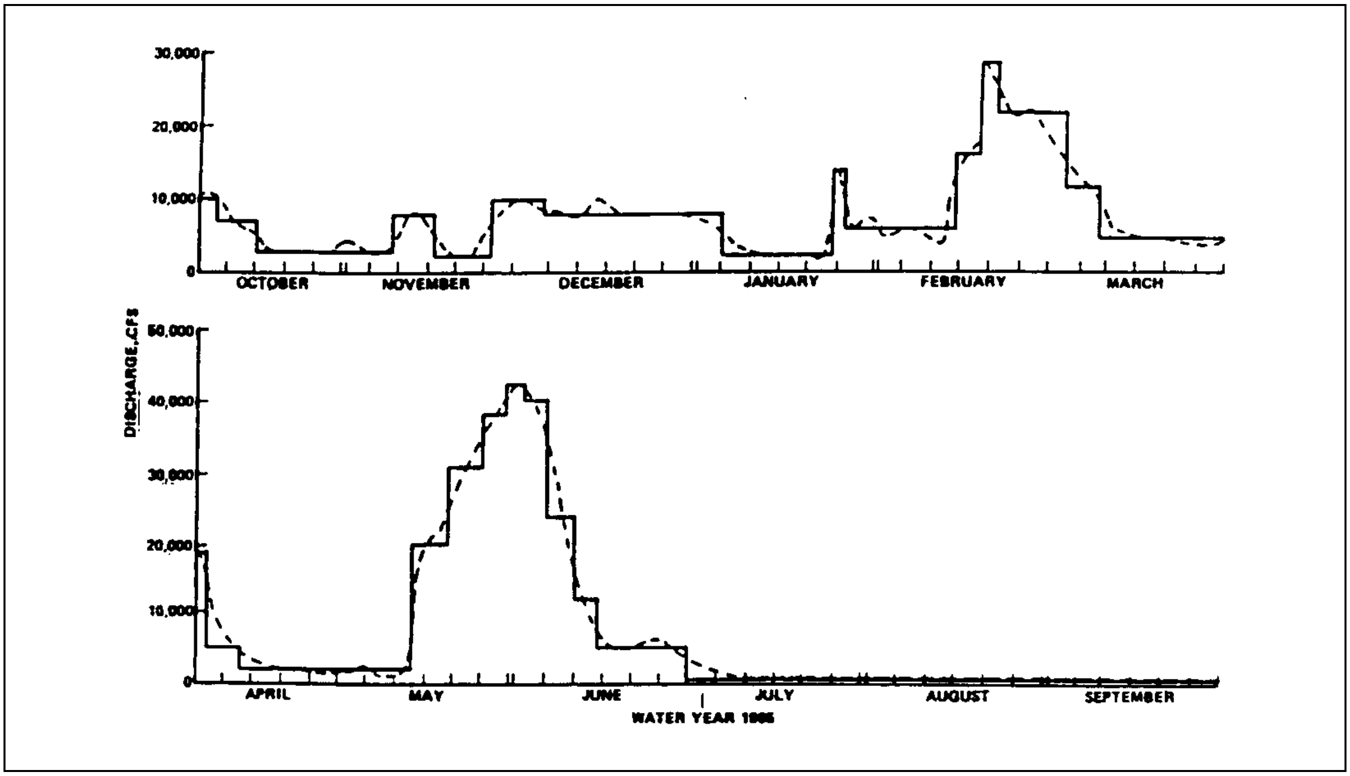

Figure 10-4. Water discharge histograph

available, the inflowing sediment boundary condition must be calculated. That is possible for sand and gravel using mobile bed hydraulics and sediment transport theory. There is no comparable theory for the wash load inflow. When making a calculation for the boundary condition, select the reach of channel very carefully. It should be one approaching the project which has a slope, velocity, width, and depth typical of the hydraulics which are transporting the sediment into the project reach. It should also have a bed surface that is in equilibrium with the sand and gravel discharge being transported by the flow. Having located such a reach, select a representative cross section for that reach. Make the calculation by particle size for the full range of water discharges in the study plan.

d. Importance of bed-material designation. In the calculation of sediment transport, the designated bed gradation controls the calculated sediment discharge. The rate of transport increases exponentially as the grain size decreases, as shown in Figure 10-7. Therefore, bed-material gradations must be determined carefully. Techniques for selecting a representative sample are discussed in paragraph 8-13 of this manual. Due to the sensitivity of transport calculations to the grain size, especially the finer sizes, Einstein (1950) recommended excluding the finest 10 percent of the sampled bed gradation for calculation of the total bed-material load.

e. Sediment inflow from tributaries. The sediment inflow from tributaries is more difficult to establish than it is for the main stem because there is usually less data. The recourse is to assess each tributary for sediment delivery potential during the site reconnaissance. For example, look for a delta at the mouths of the tributaries. Look for channel bed scour or deposition along the lower end of the tributary. Look for drop structures or other controls that would aid in stabilizing a tributary. Look for significant deposits if the tributaries have concrete lining. These observations guide the development of tributary sediment discharges.

10-14. Temporal Variations

The discussion assumes the historical water inflows, sediment concentrations, particle sizes, and tailwater rating curve will not change in the future. That assumption should be justified for each project and the appropriate modifications made.

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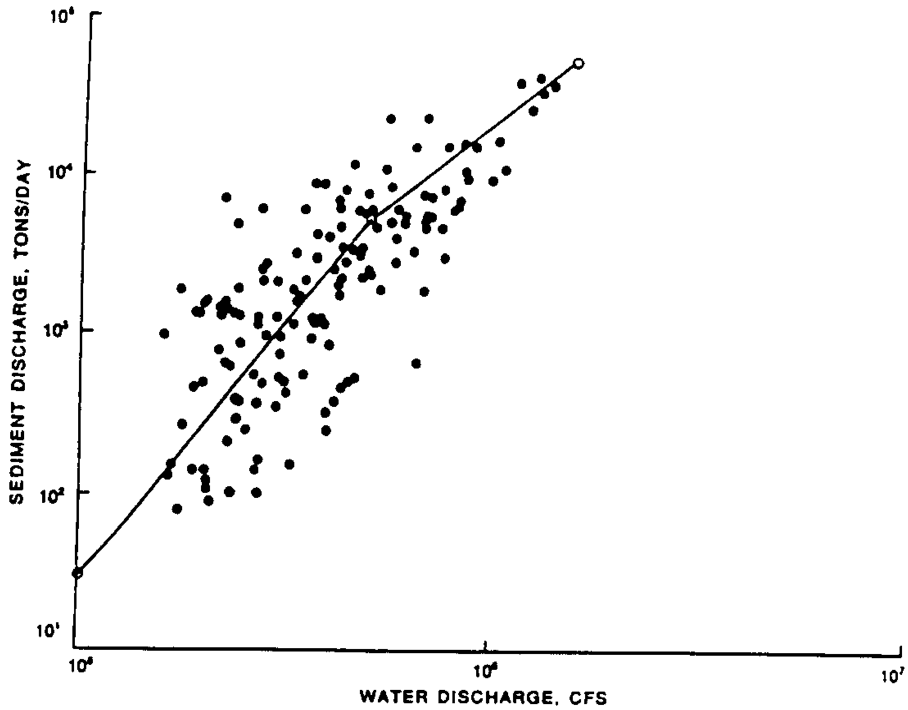

Figure 10-5. Sediment-discharge rating curve

10-15. Data and Profile Accuracy

Agreement between calculated and measured water surface elevations of +/- 0.5 ft are usually satisfactory in natural rivers. Profiles of the average bed elevation may exhibit little or no correlation with the prototype, but cross-sectional area changes should correlate with prototype behavior.

Section IV
Model Adjustment and Circumstantiation

10-16. Model Performance

Prior to using a numerical model for the analysis of a project, the model's performance needs to be confirmed. Ideally this consists of a split record test: an adjustment test and a circumstantiation test. During the adjustment test, initial boundary conditions and hydraulic coefficients are chosen such that computed results reproduce field measurements within an acceptable error range. Computed results should be compared with field measurements to identify data deficiencies or physically unrealistic values. In order to improve the agreement between observed and calculated values, model coefficients and boundary conditions are adjusted, but only within the bounds associated with their uncertainty. Model adjustment does not imply the use of physically unrealistic coefficients to force a poorly conceived model into reproducing prototype measurements. If a discrepancy between model results and prototype data persists, then either there is something wrong with the model's representation of the dominant physical processes (a model deficiency as a result of limiting assumptions), there is a deficiency in the representation of field data as model input (an application error), and/or there is something wrong with the measured data (a data deficiency). Therefore, if model adjustment cannot be accomplished through the usage of physically realistic values of the coefficients, the measured prototype data should be checked for possible errors and the numerical model (input data, basic equations, and solution algorithm) should be examined. One caution is to recognize the time scale factor. For example, when the boundary concentrations are increased, there should be a deposition trend in the interior of the model. When such a trend does not occur, it may signify that more time is needed. Extend the hydrograph until the deposition trend shows up in the calculated results. *

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Table 10-2
Distribution of Sediment Load by Grain Size Class

Water Discharge: 35,000 cfs	Total Bed Load, tons/day...................130 Total Suspended Load, tons/day.....1,500 Total Sediment Load........................1,630

Grain Size Diameter, mm	Classification	Percent Bed Load	Bed Load tons/day	Percent Suspended Load	Suspended Load, tons/day	Total Load Column (4) + (6) tons/day
(1)	(2)	(3)	(4)	(5)	(6)	(7)
< 0.0625	silt and clay	0.04	0.05	54	810	810
0.0625 - 0.125	very fine sand	0.10	0.13	10	150	150
0.125 - 0.25	fine sand	2.75	4.00	13	195	199
0.25 - 0.50	medium sand	16.15	21.00	19	285	306
0.50 - 1.0	coarse sand	13.28	17.00	4	60	77
1.0 - 2.0	very coarse sand	1.19	2.00			2
2 - 4	very fine gravel	1.00	1.00			1
4 - 8	fine gravel	1.41	2.00			2
8 - 16	medium gravel	2.34	3.00			3
16 - 32	coarse gravel	6.33	8.00			8
32 - 64	very coarse gravel	23.38	30.00			30
> 64	cobbles and larger	32.03	42.00	—	—	42
TOTAL		100.00	130.18	100	1,500	1,630

Notes:

[1] The distribution of sizes in the bed load is usually computed using a bed-load transport function and field samples of bed-material gradation. The bed-load rate is rarely measured and may have to be computed.

[2] The suspended load and its gradation can be obtained from field measurements. The bed-material portion of the suspended load may be calculated using a sediment transport function, but the wash load can only be obtained through measurement.

10-17. Model Adjustment

Model adjustment is the process of coefficient selection and input data modification that produces model simulation results that agree with prototype behavior. Adjustment involves the selection of values for fixed and movable bed coefficients plus the art of transforming three-dimensional prototype measurements into “representative data” for one-dimensional computations. ***Fixed bed coefficients*** are: roughness coefficients, which do not depend on the characteristics of the movable boundary; coefficients of contraction; coefficients of expansion; and ineffective flow area delineation. ***Movable bed coefficients*** are roughness coefficients for the movable bed, which may depend on the rate of sediment transport. Development of ***representative data*** for one-dimensional computations is not done by simply averaging a collection of samples. In terms of geometry, it is the selection of cross sections which produces the one-dimensional approximation of hydraulic parameters that will reconstitute prototype values in such a way that water and sediment movement in the model mimics that in the prototype. In terms of sedimentation, it requires the selection *

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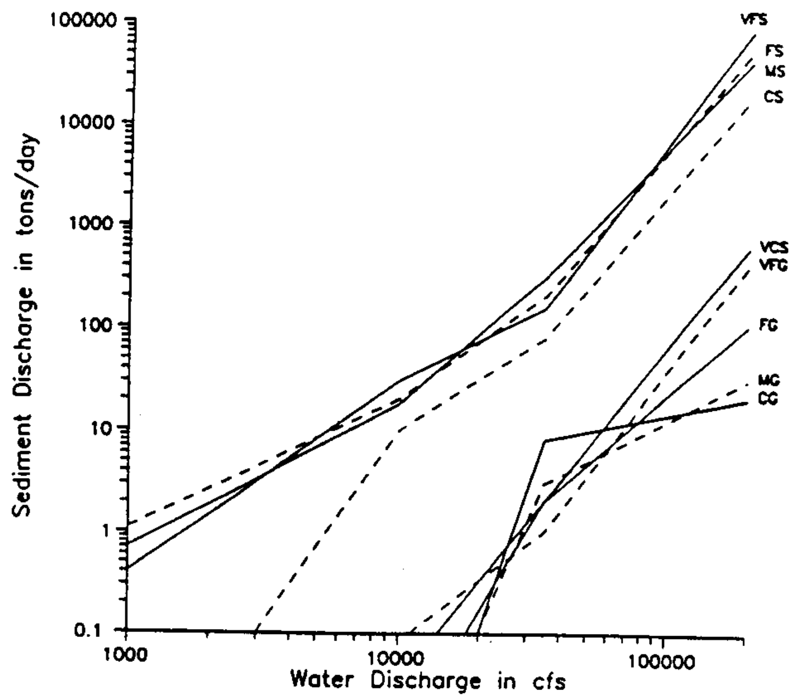

Figure 10-6. Sediment load curves

of bed-material gradation curves, the determination of the inflowing sediment discharge, and the determination of the fraction of sediment in each size class of the inflowing discharge that reflects the dominant prototype processes.

a. Roughness coefficients. The most dependable method for determining roughness coefficients for flood flows is to reconstitute measured high water profiles from historical floods. The second most dependable method is to reconstitute measured gauge records. When there are no reliable field measurements, the recourse is to use stage-discharge predictors for the movable bed portion of the cross section, as discussed in paragraph 9-11 of this manual, and calibrated photographs (Barnes 1967, Chow 1959) for the overbank and fixed bed portions. Document prototype conditions by means of photographs during the field reconnaissance.

b. Contraction and expansion losses. The information on contraction and expansion losses is more sparse than for roughness coefficients. King and Brater (1963) give values of 0.5 and 1.0 for a sudden change in area accompanied by sharp corners, and values of 0.05 and 0.10 for smooth transitions. Design values of 0.10 and 0.20 are suggested. Values often cited by the U.S. Army Corps of Engineers (USAEHEC 1990) are 0.1 and 0.3, contraction and expansion, respectively, for gradual transitions.

c. Representative data. Developing the one-dimensional representation of a three-dimensional open channel flow problem is an art. It requires one to visualize the three-dimensional flow lines in the actual problem and translate that image into a one-dimensional model. This step will often require several iterations to arrive at an acceptable model. A successful approach is to “creep” upon a solution by first running a fixed-bed model, and then adding sediment computations to simulate mobile-bed behavior.

d. Steady flow, fixed-bed tests. Start with a steady-state discharge of about bankfull. In a regime channel this is expected to be about the 2-year-flood peak discharge. Ascertain that the model is producing acceptable hydraulic results by not only reconstituting the water-surface profile but also plotting the water velocity, depth, width, and slope profiles. This test will often reveal width increases between cross sections which are greater *

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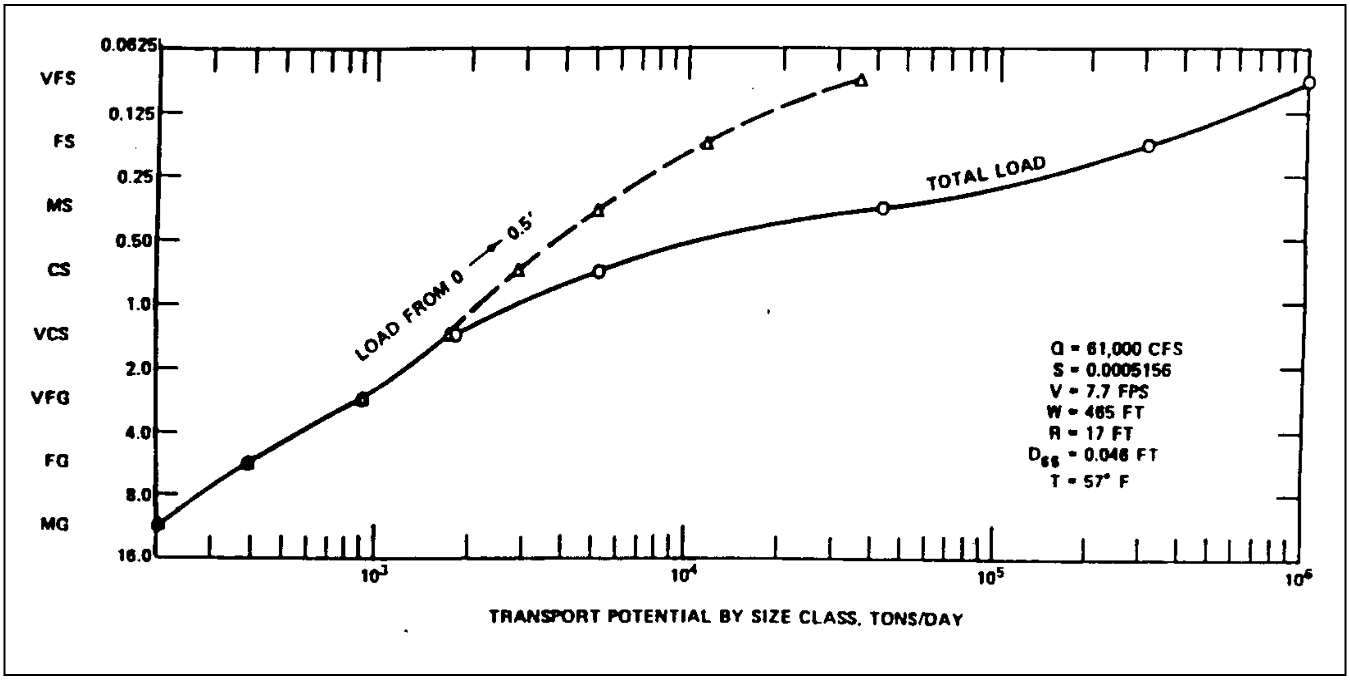

Figure 10-7. Variation of sediment transport with grain size

than the expansion rate of the fluid and, therefore, require conveyance limits. Extremely deep bend sections will occasionally indicate velocities which are not representative for sediment transport around the bend, and the recourse is to eliminate them from the model. The results from running this discharge will also give some insight as to how close the existing channel is to a "normal regime." That is, if there is overbank flow, justify that it also occurs in the prototype and is not just a "numerical problem." It is useful to repeat this steady-state, fixed-bed test for the maximum water discharge to be used in the project formulation before moving on to the movable-bed tests. The key parameters to observe are water-surface elevations, flow distribution between channel and overbanks, and velocities. However, each study is unique, and one should not regard this paragraph as a complete checklist of suggestions.

e. Steady flow, movable-bed tests. It is also useful to determine the model performance for the bankfull flow with a movable bed. Again, if the channel is near regime, this should be about a dominant discharge and result in very little aggradation or degradation. Before focusing on sediment transport, however, demonstrate that the channel roughness coefficients are appropriate for the movable boundary. Make whatever adjustments are necessary to ensure that the roughness coefficients for the streambed portion of the cross section are in reasonable agreement with that from stage-discharge predictors. Also, the sediment transport rate will usually be higher at the beginning of the simulation than it is for subsequent events because there is usually an abundance of fines in the bed samples which will be flushed out of the system as the bed layers are formed. The physical analogy is starting water to flow down a newly constructed ditch or a flume with a newly placed sand bed. It is important to balance the sizes in the inflowing bed-material load with transport potential and bed gradation. The scatter in measured data is usually sufficiently great to require smoothing, but the adopted curves should remain within that scatter.

f. Consequences of inaccurate roughness coefficients. In fixed-bed hydraulics, a range of roughness coefficients is typically chosen. The low end of that range provides velocities for riprap design and the high end provides the water-surface profiles for flood protection. In movable-bed studies such an approach is usually not satisfactory because of the feedback linkage between sediment transport and hydraulic roughness. Use of roughness coefficients which do not agree with that linkage can result in either too much degradation or too much aggradation.

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* 10-18. Model Circumstantiation Process

The model adjustment process is conducted to ensure that the model will reconstitute trends which have been observed in the prototype. The circumstantiation process is to change boundary conditions and rerun the model without changing its coefficients. This step establishes whether or not the coefficients which were selected in the model adjustment process will continue to describe the prototype behavior when applied to events not used in their selection. The inflowing sediment load should be changed as necessary to correspond with that during the time period selected for the circumstantiation process. This step does not ensure that the model will accurately predict prototype behavior for all boundary conditions, but it does provide additional confidence (circumstantial evidence) in model results.

10-19. Processes to Observe

a. It is important to base model performance on those processes which will be used in decision making. These usually include the water-surface profiles, flow distributions between channel and overbanks, water velocities, changes in cross-sectional area, sediment discharge passing each cross section, and accumulated sediment load, by size class, passing each cross section. A one-dimensional model may not precisely reconstitute thalweg elevations because the thalweg behavior is a three-dimensional process. Therefore, use cross-sectional end area changes and not thalweg elevation in the adjustment and circumstantiation tests. Three types of graphs should be plotted to show results. The first is "variable versus elevation." An example, the comparison of calculated stages with the observed rating curve, is shown in Figure 10-8. The second graph is "variable versus distance" for a point in time as illustrated by the water-surface and bed-surface profiles in Figure 10-9. The third is "variable versus time" at a selected cross section along the model, Figure 10-10.

b. The hydrograph used in adjustment and circumstantiation tests may extend for several years. If so, select only a few key values per year to plot. Plot the calculated water-surface elevations at all gages in the study area as well as the observed elevations that occurred at the same points in time. Evaluate model performance by computing the mean of the absolute values of error. Of course, the lower the mean value of error, the better the performance. Unfortunately, performance quality is defined by problem-specific characteristics and will probably differ from problem-to-problem. Good engineering judgment should be used to determine when the model's performance is, in fact, satisfactory or when the model requires additional adjustment.

10-20. Correcting Poor Model Performance

If the model is reproducing processes in the prototype, the key parameters should match reasonably well. These include water depths, measured velocities, measured sediment concentrations within the study reach, and bed gradations. Calculated bed gradations can be compared with sampled bed gradations by plotting the calculated active-bed gradations for computational reaches. A good way to check the reasonableness of inflowing sediment loads is to compare calculated and measured bed gradations downstream from inflow points. The following suggestions illustrate the thought process that should occur when there is an unacceptable deviation.

a. First, position the upstream boundary of the model in a reach of the river which is stable, and be sure the model exhibits that stability. That means the upstream cross section should neither erode nor deposit. Tend to hydraulic problems starting at the downstream end and proceeding toward the upstream end of the model. Reverse that direction for sediment problems. Do not worry about scour or deposition at the downstream end of the model until it is demonstrating proper behavior upstream from that point.

b. Second, be sure the model is numerically stable before adjusting any coefficients or processes.

c. Once the above two conditions are met, focus attention on overall model performance. Check the boundary conditions to ascertain that the particle size classes in the inflowing sediment load have been assigned "representative" concentrations. Use depth and gradation of the bed-material reservoir to determine if the model bed matches the prototype. Make plots for several different times because the gradation of the model bed will vary with the inflowing water-sediment mixture. Correct any inconsistencies in these data and try another run. If the problem persists, check the field data for possible rock outcroppings and check calculated profiles for possible errors in nearby sections.

d. If calculated transport rates are too high, check prototype data for a gravel deposit which could be forming an armor layer.

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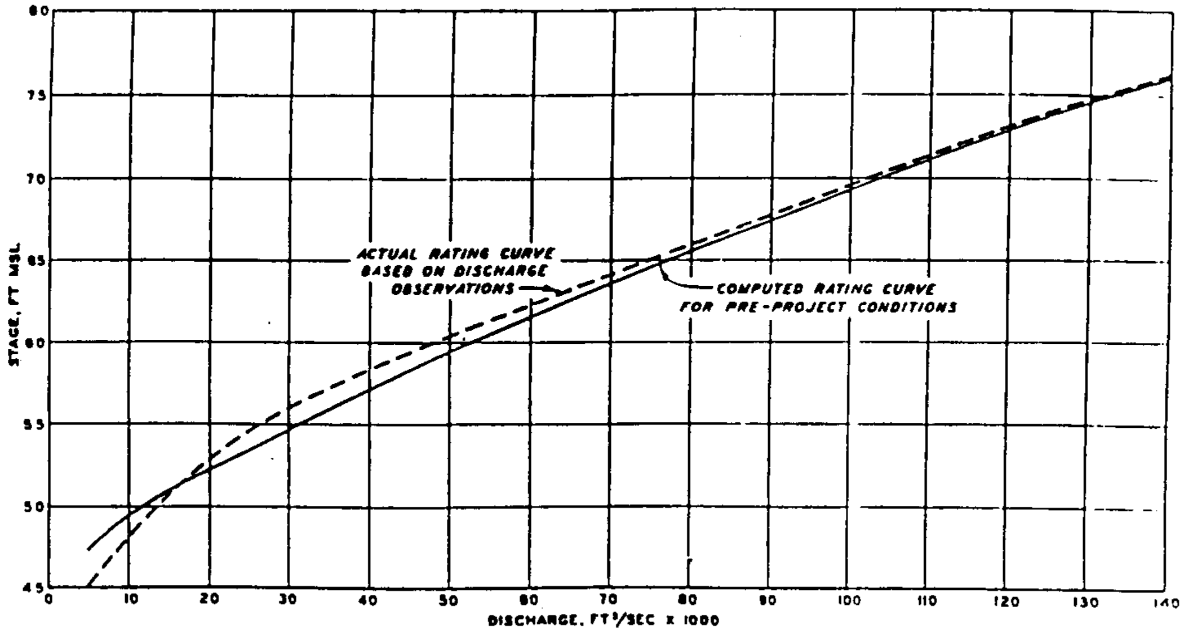

Figure 10-8. Reconstituting the stage-discharge rating curve

e. If calculated rates of deposition are too high or rates of erosion are too low, check top bank elevations and ineffective flow limits to ensure that the model is not allowing so much flow on the overbanks that the channel is becoming a sink.

f. Finally, if none of the above actions produce an acceptable performance, then change the inflowing sediment load. First use a constant ratio to translate the curve without rotation. If that is not successful, rotate the curve within the scatter of data.

10-21. Development of Base Test and Analysis of Alternatives

The most appropriate use of a movable-bed simulation is to compare an alternative plan of action with a base condition.

a. *The base test.* In most cases the base condition is the simulated behavior of the river under a "no action future." In a reservoir study, for example, the base test would be used to calculate the behavior of the reservoir reach of the river without the dam in place. In most cases, the base test simulation should show little or no net scour or deposition. These are the river reaches which are near equilibrium (where scour approximately equals deposition) under existing conditions.

b. *Plan tests.* The project alternatives can be simulated by modifying the base data set appropriately. In case of a reservoir, a dam can be simulated by inserting "operating rule data" into the base test model. For a channel improvement project, cross-sectional geometry and roughness can be changed. If a major change is required, make the evaluation in steps. Avoid changing more than one parameter at a time because that makes the results difficult to interpret. For example, it is best to analyze a channel modification project in two steps. First, change the hydraulic roughness values and simulate future flows in the existing geometry. It will be necessary to select and justify the roughness coefficients for future conditions. Justify values by consideration of proposed design shapes, depths, channel lining materials, proposed vegetation on the overbanks, probable channel debris, and calculated riprap requirements. Secondly, insert the modified cross sections and complete the analysis by simulating the alternatives to be tested. Also, select the contracting and expansion coefficients. Use model results as an aid in predicting future conditions; rely heavily on engineering judgment and look for surprises in the calculated results. These "surprises" can be used by the experienced river engineer to locate data inadequacies and to better understand the behavior of the prototype system. Any unexpected response of the model should be justified very carefully before accepting the results.

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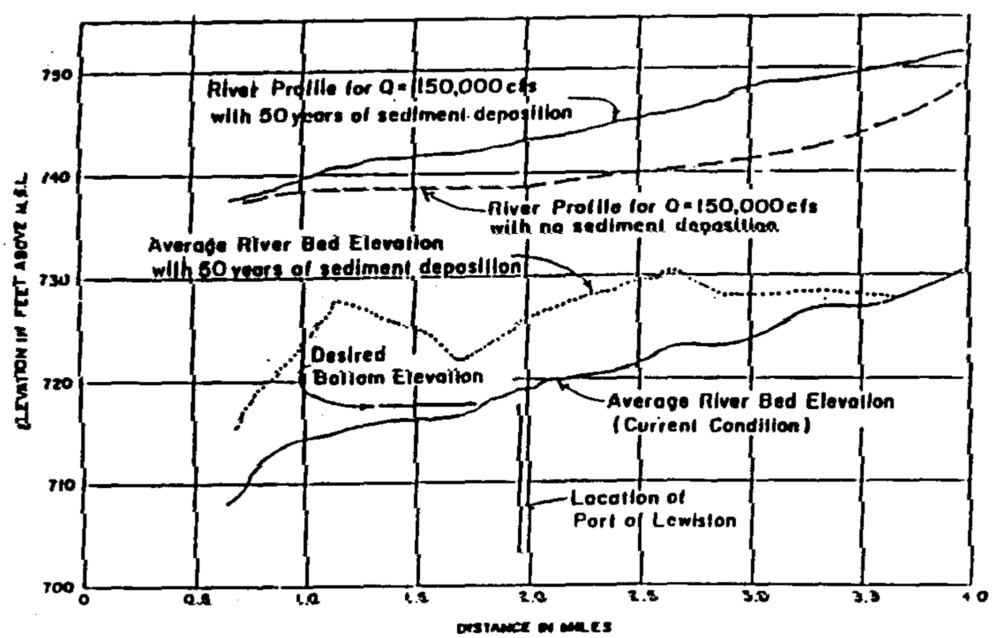

Figure 10-9. Water-surface and bed-surface profiles

c. Presentation of results. Results should be presented in terms of change from the base case rather that absolute values. This will provide an assessment of the impacts of proposed projects.

d. Sensitivity tests. It is usually desirable during the course of a study to perform a sensitivity test. Quite often certain input data (such as inflowing sediment load) are not available, or might be subject to substantial measurement error. The impact of these uncertainties on model results can be studied by modifying the suspected input data by one or two standard deviations and rerunning the simulation. If little change in the simulation results, the uncertainty in the data is of no consequence. If large changes occur, the input data need to be refined. Refinement should then proceed using good judgment and by modifying only one parameter or quantity at a time so as to be able to see the exact effect that overall changes may have. Sensitivity studies performed in this manner will provide sound insight into the prototype's behavior and will lead to the best model description of the real system.

Section V
Computer Programs

10-22. Introduction

Many computer programs are available for movable boundary simulations, and more will be created in the future. The two programs recommended for use for U.S. Army Corps of Engineers sedimentation studies are briefly discussed below. For any particular study, the need to use a different program or suite of programs may be justified. This need should be defined early in the study.

10-23. Scour and Deposition in Rivers and Reservoirs (HEC-6)

The HEC-6 code (USAEHEC 1993) is a one-dimensional movable-bed sediment model. It was formulated around Einstein's basic concepts of sediment transport; however, it is designed for the nonequilibrium case. Einstein did not address the nonequilibrium condition, but his "particle
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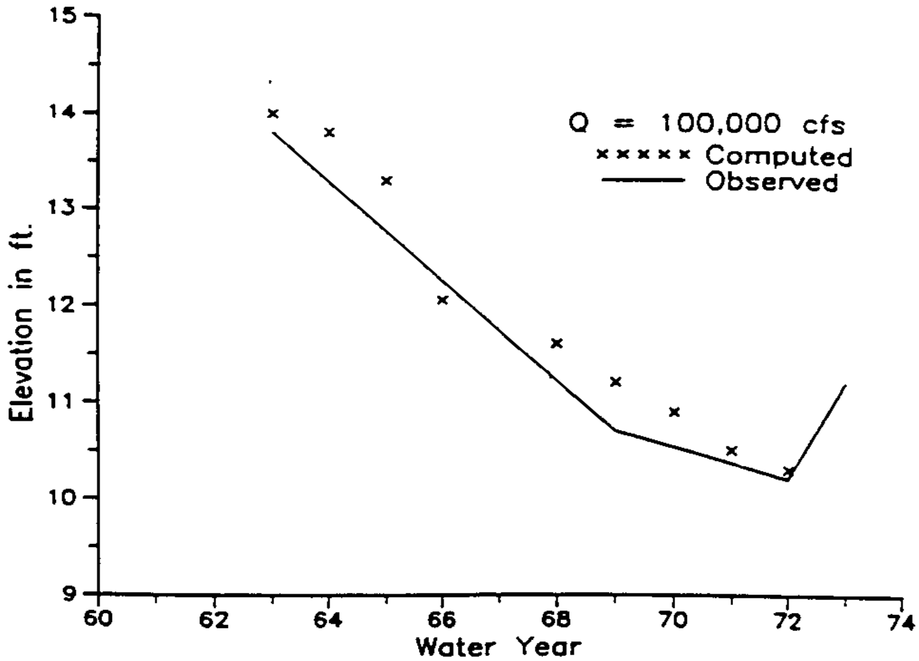

Figure 10-10. Water-surface trend plot (specific gage plot)

exchange" concept was extended by noting that when sediment is in transport there will be a continual exchange between particles in motion and particles on the bed surface. The residue may be measurable as in the case of the "bed material load," or it may be unmeasurable, as in the case of "wash load." The stability of particles on the bed surface may be related to inertia, as in the case of noncohesive particles, or that stability may be primarily electrochemical, as in the case of cohesive particles. Forces acting to entrain a particle may be primarily gravity-induced, as in the case of flow in inland rivers, or the forces may be combinations of energy sources such as gravity, tides, waves, and density currents, as in the coastal zone. Different types of sediment require different entrainment functions depending upon the propensity of the sediment to change hydrodynamic and physical properties of the flow and upon the sensitivity of the sediment type to water temperature and chemistry.

a. Equations of flow. The equations for conservation of energy and water mass are simplified by eliminating the time derivative from the motion equation which leaves the gradually varied steady flow equation. It is solved using the standard step method for water-surface profiles. The following terms are included:

$$\frac{\partial h}{\partial x} + \frac{\partial \left(\frac{\alpha V^2}{2g} \right)}{\partial x} = Se \qquad \text{(Conservation of energy)} \tag{10-4}$$

where

g = acceleration due to gravity

h = water surface elevation

Se = slope of energy line

V = average flow velocity

x = direction of flow

α = correction for horizontal distribution of flow velocity

$$Q = VA + Q_L \qquad \text{(Conservation of water)} \tag{10-5}$$

*

* where

A = cross-sectional area of flow

Q_L = lateral or tributary inflow

Q = main stem water discharge downstream from tributary

V = main stem average water velocity upstream from Q_L

b. Friction and form losses. Both friction and form losses are included in the slope of the energy line; bed roughness is prescribed with Manning's *n* values. The model does not have a bed-form roughness predictor but *n* values may vary with water discharge. HEC-6 has an option which uses the Limerinos equation to calculate the channel Manning's *n* value.

c. Equation of sediment continuity. The Exner equation is used for conservation of sediment:

$$\frac{\partial Q_s}{\partial x} + B_s \frac{\partial Y_s}{\partial t} + q_s = 0 \quad (\textit{Conservation of sediment}) \tag{10-6}$$

where

B_s = width of bed sediment control volume

Q_s = volumetric sediment discharge rate

q_s = lateral or tributary sediment discharge rate; (-) is an inflow (+) is an outflow

t = time

y_s = bed surface elevation

d. Numerical integration scheme. The conservation of energy, conservation of water, and conservation of sediment equations are solved numerically using an explicit, finite difference computation scheme. Figure 10-11 shows a definition sketch, and the numerical forms of the equations are presented below.

$$h_2 = h_1 + \left(\frac{\alpha V^2}{2g}\right)_1 - \left(\frac{\alpha V^2}{2g}\right)_2 + H_L \tag{10-7}$$

$$Y_s(t) = Y_s(t-1) - \frac{\Delta t}{B_s}\left(\frac{(Q_{so} - Q_{si})}{(0.5 * L)} + q_s\right) \tag{10-8}$$

where

h = water surface elevation

H = energy elevation

H_L = head loss

Δt = computation time interval

L = reach length at this computation point (distance between cross-sections 1 and 3)

Q_{si} = sediment inflow to reach

Q_{so} = sediment outflow from the reach

q_s = lateral, or tributary, sediment load; outflow (+) and inflow (-)

$Y_s(t)$ = elevation of bed at time step t

$Y_s(t\text{-}1)$ = elevation of bed at time step t-1

and subscripts 1, 2, and 3 refer to cross-sections 1, 2, and 3, respectively.

e. The inflowing sediment load is prescribed as a boundary condition. The initial values of B_s and $Y_s(t\text{-}1)$ are known from cross-sections. By adapting transport functions for Q_{so}, the only unknown is $Y_s(t)$.

f. Sediment transport potential. In the HEC-6 numerical model, sediment transport formulas are restructured to adapt them for sediment movement modeling based on observations recorded by (Einstein 1950). Sediment transport potential for a size class is calculated assuming that the bed is composed entirely of that specific size class. This is based on the premise that a water discharge has the potential to move sediment whether or not sediment particles are present in the flow or on the bed. There are several sediment transport options in the HEC-6 numerical model. Given the premise that all transport capacity formulas apply to the equilibrium *

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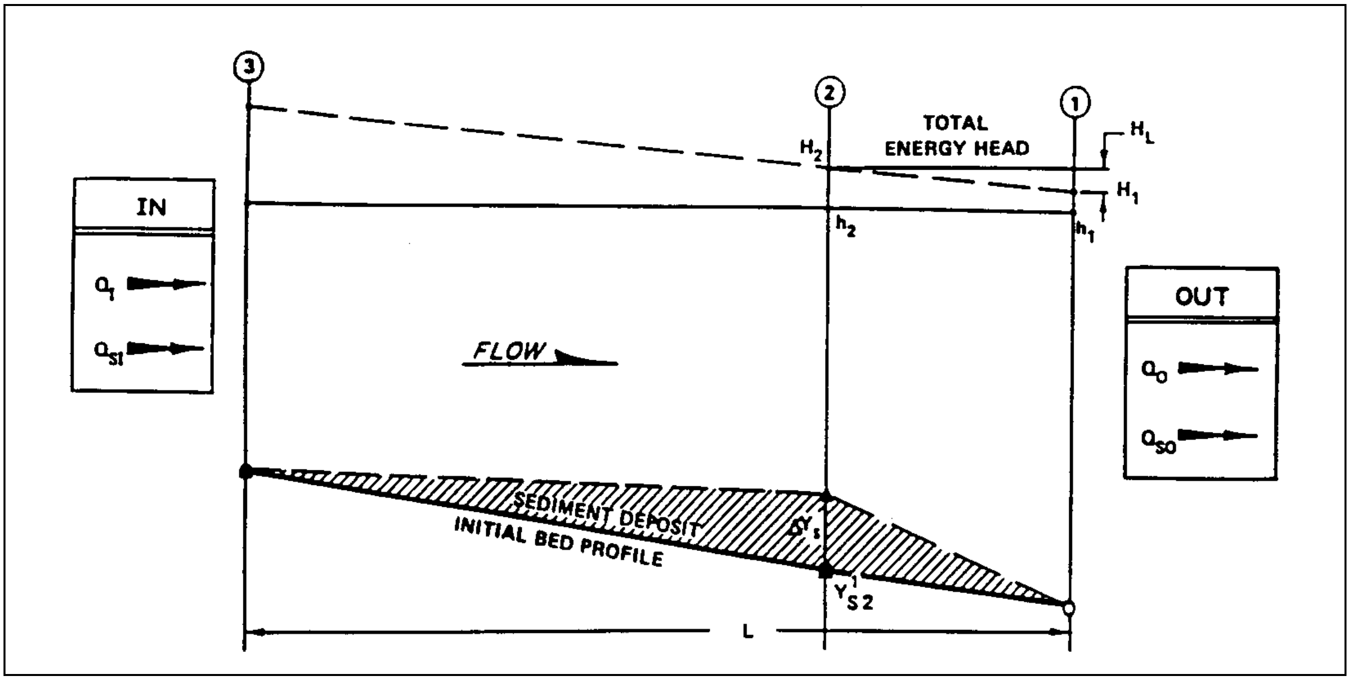

Figure 10-11. Numerical integration scheme

condition as described by Einstein, the probability that grains are present is equally significant to all even if they were not developed as stochastic formulations.

(1) Transport potential is computed for each cross-section, whether or not sediment is present on the bed surface. Subsequently, particle availability can be evaluated and expressed as a fraction of the bed surface, f_i. Availability and transport potential can then be combined during the solution of the Exner equation to give transport capacity (Q_{SO}) as follows:

$$Q_{SO} = \sum_{i=i}^{N} f_i \, Q_{Pi} \tag{10-9}$$

where

f_i = fraction of bed surface particles in size class i by weight

Q_{Pi} = sediment transport potential for size class i

n = number of size classes

(2) Transport potential can be very large for the finer particle sizes, which makes the transport capacity very sensitive to f_i. This may lead to numerical instability in the explicit solution of the sediment continuity equation which accounts for removal of specific grain sizes from the bed according to their transport capacity. The hydraulic sorting algorithm in HEC-6 breaks the computational time step into increments for solution of the sediment continuity equation, which dampens possible numerical shocks to the solution. A new value for f_i is calculated at the end of each increment. Transport capacity, then, is the accumulation of the sediment discharged during each increment over the computational time step.

(3) The concept of transport potential is what allows HEC-6 to analyze the nonequilibrium conditions such as sand moving over a gravel bed or sand and gravel moving over a hard bottom channel. The key is maintaining a control volume in the bed sediment reservoir in which the gradation of sediment is continuously updated as sediment is deposited into or scoured out of the bed. Erosion and entrainment processes seem strongly dependent on the uniformity, or lack of it, of the bed mixture. An equilibrium depth concept was established by combining flow intensity with the stability of grain sizes (USAEHEC 1993). It extends into the bed forming an active layer depth. Sediment particles are added to that layer when deposition occurs and removed from it when erosion occurs. The active layer is exchanged with the inactive layer, which lies beneath it, when the thickness becomes

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* too great. It is resupplied from the inactive layer as follows.

(4) Erosion, and removal of particles from the active layer, occurs when transport capacity exceeds the inflowing sediment concentration in a size class. The process works in increments equal to two particle diameters each. A complex sorting algorithm was developed to logically feed sediment mixtures from the inactive layer into the active layer. This process depends on availability and proceeds at a rate that recognizes the presence of a cover layer on the bed surface. The cover layer is hypothesized to develop because the transport functions move larger particles more slowly than smaller ones in the mixture and, therefore, the larger particles collect on the bed surface until an excess transport capacity removes them by erosion.

g. Time for entrainment. The time that is required for a water discharge to entrain a sufficient weight of sediment from the streambed to achieve the equilibrium condition of transport capacity is referred to as "time for entrainment." Research is needed to quantify that value. Meanwhile, some value is required, and Thomas (USAEHEC 1993) made the assumption that it could be related to flow depth. Sediment entrainment is constrained by the entrainment time in the HEC-6 numerical model.

h. Time for deposition. The characteristic time for deposition is calculated from the particle settling velocity, the flow velocity, and the water depth. In cases where the reach length is insufficient to allow for settling of a particular size through the entire water column, an adjustment is made to deposition quantities in the HEC-6 numerical model.

i. Armoring. When an armor layer develops on the bed surface, sediment particles which are smaller than the smallest size in that armor layer are no longer available from the bed source. However, f_i is a function of both the bed and the inflowing load; therefore, the inflowing load provides an exchange of particles with the bed, which creates a new f_i. That exchange between the bed and water column continues until a value for Q_{so} has been calculated for time ΔT. Gessler's (1971) work is used to determine the stability of an armor layer including particles which are larger than those transported. The equation for stability is

$$BSF = \frac{\sum_{i_{min}}^{i_{max}} P^2 f_i d_i}{\sum_{i_{min}}^{i_{max}} P f_i d_i} \quad \text{(Bed Stability Factor)} \qquad (10\text{-}10)$$

where

P = probability grains will stay

f_i = fraction of ith size class present

d_i = grain-size class interval

BSF = bed stability factor

Stability is tested at the beginning of each discharge event and if *BSF* is less than 0.65, the armor layer is destroyed. The reformation process begins immediately and is controlled by flow intensity and the inflowing sediment load.

j. The application of HEC-6. The input data file is prepared prior to accessing the program. Hydraulic computations begin at the downstream boundary and proceed cross section by cross section to the upstream boundary. Hydraulic parameters are computed and saved for sediment computations. Sediment movement computations begin at the upstream boundary and proceed section by section to the downstream boundary. At each section at the beginning of a computational time step, the volume of sediment in the bed that is available for exchange with the water column is determined. First, the stability of the armor layer stability is tested, then the equilibrium depth and active layer thickness are calculated, and an appropriate quantity of bed sediment is exchanged between the active and inactive layers. The sediment continuity equation can be solved several times during a computational time step to account for changes in the bed-material gradation of the active layer. These incremental solutions are called exchange increments and the number is specified by the user. Sediment inflow during the computational time step is equally proportioned, by size class, into each exchange increment. During each exchange increment the inflowing mass is compared with the transport capacity of each size class through the reach, and if either deposition or erosion is indicated, the outflow from the reach is adjusted by that *

* amount. The weight of the active layer is recalculated after each exchange increment calculation and the new active layer bed gradation is determined. This process is repeated for each exchange increment to numerically integrate the erosion, entrainment, transportation, and deposition during the computation time step. After the sediment movement computations are completed the resulting weight of sediment is converted to a volume, considering consolidation, and the cross section elevations are changed accordingly. The program then reads in the next hydrologic event and the process is repeated.

10-24. Open Channel Flow and Sedimentation (TABS-2)

a. Purpose. The purpose of the TABS-2 system (Thomas and McAnally 1985) is to provide a complete set of generalized computer programs for two-dimensional numerical modeling of open-channel flow, transport processes, and sedimentation. These processes are modeled to help solve hydraulic engineering and environmental problems in waterways. The system is designed to be used by engineers and scientists who need not be computer experts.

b. Description. TABS-2 is a collection of generalized computer programs and utility codes integrated into a numerical modeling system for studying two-dimensional hydraulics, transport, and sedimentation problems in rivers, reservoirs, bays, and estuaries. A schematic representation of the system is shown in Figure 10-12.

c. Uses. It can be used either as a stand-alone solution technique or as a step in the hybrid modeling approach. The basic concept is to calculate water-surface elevations, current patterns, dispersive transport, sediment erosion, transport, and deposition, resulting bed surface elevations, and feedback to hydraulics. Existing and proposed geometry can be analyzed to determine the impact of project designs on flows, sedimentation, and salinity. The calculated velocity pattern around structures and islands is especially useful.

d. Basic components of system.

(1) "Two-Dimensional Model for Open Channel Flows," RMA-2V.

(2) "Sediment Transport in Unsteady Two-Dimensional Flows, Horizontal Plane," STUDH.

(3) "Two-Dimensional Model for Water Quality," RMA-4.

e. RMAV-2V. RMA-2V is a finite element solution of the Reynolds form of the Naiver-Stokes equations for turbulent flows. Friction is calculated with Manning's equations, and eddy viscosity coefficients are used to define turbulence characteristics. A velocity form of the basic equation is used with side boundaries treated as either the slip or static. The model automatically recognizes dry elements and corrects the mesh accordingly. Boundary conditions may occur inside the mesh as well as along the edges.

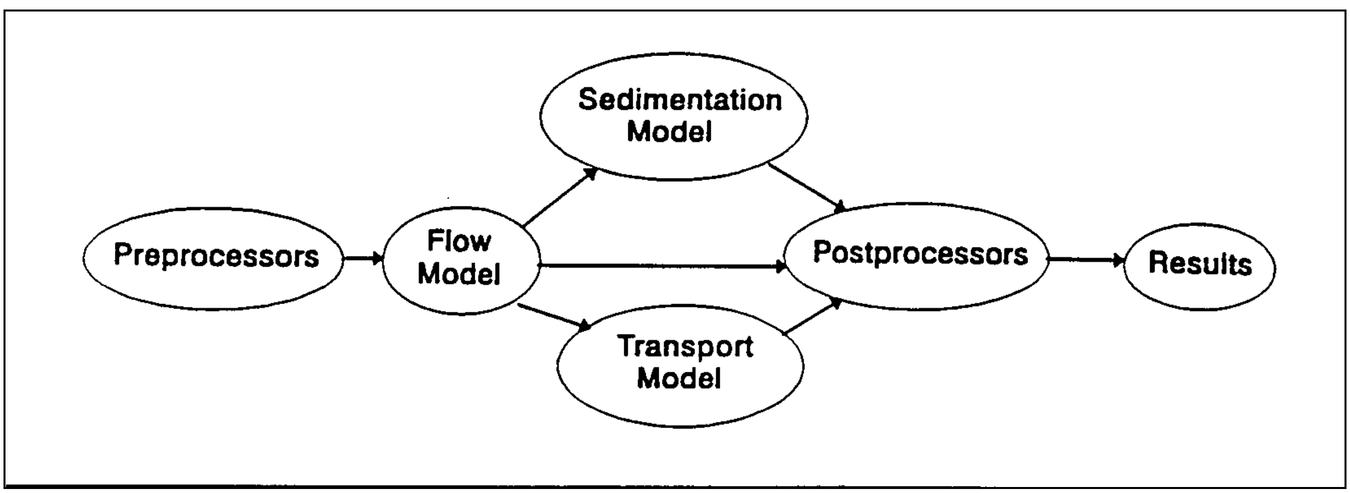

Figure 10-12. TABS-2 schematic

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* *f. STUDH.* The sedimentation model STUDH solves the convection-diffusion equation with bed source terms. These terms are structured for either sand or cohesive sediments. The Ackers-White sediment transport function is used to calculate a sediment transport potential for the sands from which the transport capacity is calculated based on availability. Clay erosion is based on work by Partheniades, and the deposition of clay utilizes Krone's equations. Deposited material forms layers, as shown in Figure 10-13, and bookkeeping within the STUDH code allows up to 10 layers at each node for maintaining separate material types, deposit thickness, and age. The code uses the same mesh as RMA-2V.

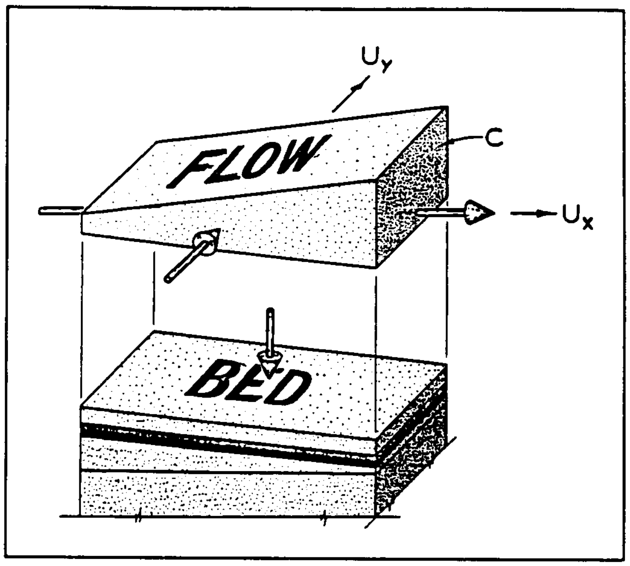

Figure 10-13. Bed layering in STUDH

g. RMA-4. Transport calculations with RMA-4 are made using a form of the convection-diffusion equation that has general source-sink terms. Up to seven conservative substances or substances requiring a decay term can be routed. The code uses the same mesh as RMA-2V.

h. System or stand-alone programs. These codes can be used as a system or each of them can be used as a stand-alone program.

i. Utility programs. A family of utility programs was developed to facilitate the preparation of input data and to aid in analyzing results.

Section VI
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